Dubovikova, Nataliia; Karcher, Christian; Kolesnikov, Yuri

Velocity and flow rate measurement of liquid metal by contactless electromagnetic Lorentz force technique

Original published in:

IOP conference series / Materials science and engineering. - London [u.a.] : Institute of Physics. - Bd. 143.2016, Article ID 012022 , insges. 4 S.

ISSN (online): 1757-899X
ISSN (print): 1757-8981
DOI: 10.1088/1757-899X/143/1/012022
URL: http://dx.doi.org/10.1088/1757-899X/143/1/012022
[*Visited:* 2016-10-19]

IOP Conf. Series: Materials Science and Engineering **143** (2016) 012022 doi:10.1088/1757-899X/143/1/012022

Velocity and flow rate measurement of liquid metal by contactless electromagnetic Lorentz force technique

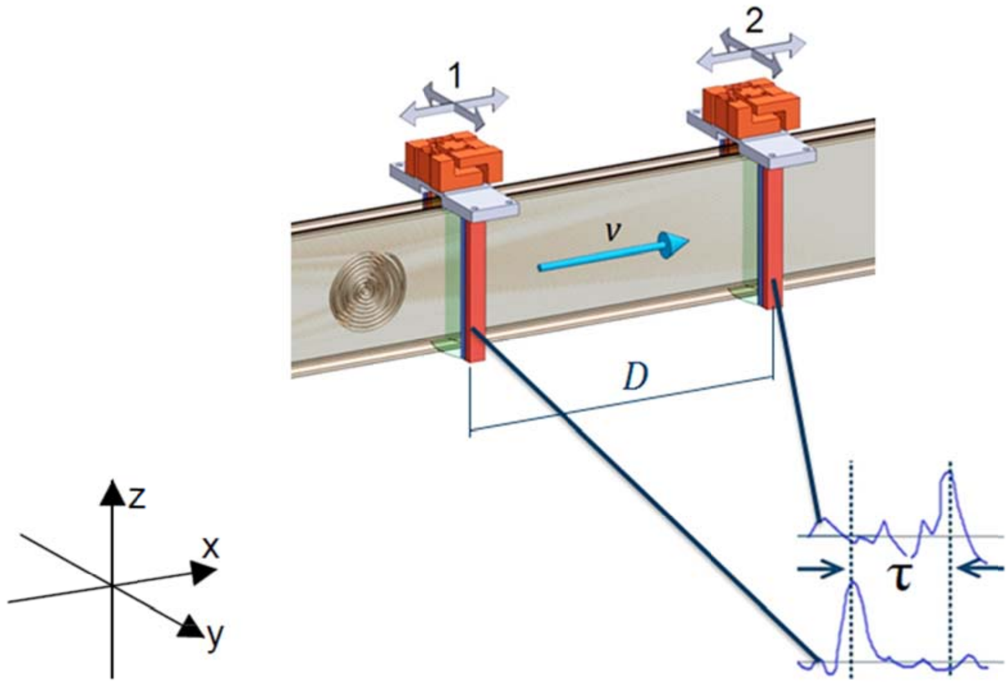
N Dubovikova, C Karcher and Y Kolesnikov
Technische Universität Ilmenau
Institute of Thermodynamics and Fluid Mechanics
P.O.Box 100565, D-98684 Ilmenau, Germany

E-mail: nataliia.dubovikova@tu-ilmenau.de

Abstract. Providing flow analysis in case of aggressive and hot liquids is a complicated task, especially when liquid's composition and, hence, its physical properties, are unknown. Contactless techniques are the most promising methods for liquid metal flow rate control and some of these methods are based on electromagnetic induction of breaking force acting on an electrically conductive fluid which is moving through a magnetic field. One of the techniques is time-of-flight Lorentz force velocimetry (LFV). By using the method one can estimate volumetric flow rate without knowing of electrical conductivity, magnitude of magnetic field or characteristic dimension. The most important and crucial challenge within the technique is detection of small fluctuations of Lorentz force value. In this article we will focus on application and investigation of time-of-flight LFV.

1. Introduction

Electromagnetic flow meters find practical use during several decades for laboratory and industrial flows implying on the principle known since Faraday time [1]. Further, the theory of electromagnetic flow meters has been developed and comprehensively summarized by Shercliff [2]. From the magnetohydrodynamics it is well known that the relative motion of an electrically conducting material and magnetic field lines induces electric currents in the conductor. This principle forms the basis of electromagnetic flow investigation and flow measurements. According to main principle of electromagnetic velocimetry, electromotive force is generated within conductive liquid that moves in magnetic field; the force acts in orthogonal direction to movement and magnetic field lines and brakes relative motion of conductive body and magnetic field. One of the fields, where the electromagnetic principle can be successfully applied, is the investigation of conductive fluids flow rate. Providing of velocimetry or flow rate measurements in case of aggressive and hot fluids like liquid metals – is a complicated task. Liquid metals are not transparent to use any optical methods, and conditions inside them make it not possible to employ any mechanical probes. Therefore contactless techniques are the most promising methods for liquid metal's flow rate control. The method of electromagnetic flow control we present here - Time-of-flight Lorentz force velocimetry [3]. The technique (figure 1) is based on difference between two force signals that are measured by Lorentz force flow meters. The difference occurs by a vortex, that moving with a flow through magnetic field of both flow meters one by one. It is well known principle to use vortices as signal particles, but usually contact elements like electrodes in conductive fluids [4] or piezo sensors in commercial vortex shedding flow meters [5] are applied for vortex detection. These methods have significant disadvantage for liquid metal flow measurements – they need mechanical contact between detector and a liquid.



1, 2 – flow meters, D – distance between flow meters, τ – time delay between disturbances
Figure 1. The principle of time-of-flight Lorentz force velocimetry

The time-of-flight Lorentz force flow meter is a system of contactless sensors and consist of two permanent magnets, rigidly connected to precise force sensor, so when naturally or artificially created vortex is moving through their magnetic field, it disturbs velocity and, hence, the measured Lorentz force. The distance between measurement systems D is known, time shift τ between disturbances (peaks of two signals) can be obtained from cross-correlation function of force signals. With this data, flow rate of liquid metal can be calculated by velocity definition: distance per time multiplying duct cross-section area A:

$$\boldsymbol{Q = Av = Ak\frac{D}{\tau}}$$

where k –coefficient, obtained experimentally for every specific liquid and duct.

2. Measurement results

Our measurements were performed under next conditions and materials: the GaInSn (gallium, indium and tin alloy) is used as experimental fluid, the electromagnetic pump generates flow with Reynolds numbers from 4000 till 60000. The duct has cross-section 80 mm height per 10 mm width.
3D force sensors have measurement range 2 N, so magnet holding system should be as light as possible to not overload strain gauge sensor component in gravity direction, and the goal was reached by applying standard aluminium profiles for construction. Besides this, the magnet holding system allows mount permanent magnets with 1 mm distance to the duct, which increased sensitivity of force measurement.
The current way of signal processing contains three main steps: segmentation, filtration and correlation. Six force signals are obtained from two 3D strain gauge sensors – in x-direction (along the flow), in y-direction (orthogonal to the flow) and in z-direction (gravity line). Each experiment is repeating three times and least one minute, that is sufficient to get time delay in ms range. The

obtained signal divided into three parts 20 s each. It is made to avoid the influence of random outer noise. The received signal segments undergo band-pass filtering in low frequency range (3 5 Hz, 4 6 Hz, 5 7 Hz and 6 8 Hz) and the cross-correlation functions of alignment pairs of filtered signals (x1x2, y1y2 and z1z2) gives the desired value of time delay.
The time delay values, calculated by cross-correlation of x- and y-directions, don't represent change of velocity with increase of pump rotation frequency and, thus, cannot be used in velocity estimation. In x-direction constant bulk flow force is in evidence and it is a complicated task to distinguish useful signal from strong turbulent disturbances. In y-direction case flow is parallel to magnetic field lines and if this occurs there is no Lorentz force generation possible. The only component, that shows visible change of time delay during experiment, is z-component of force, so the mean velocity was estimated by this component.
Experiments were performed in four positions of measurement system:
- normal position – magnetic field lines penetrate all height of the duct;
- half position – magnetic field influence half duct height;
- with artificially created disturbances;
- with naturally appeared disturbances.

The half position measurements were performed to check influence of different flow meters mounting on non-flow direction components of force. Flow meters were mounted for the test in such way that ends of magnets were situated over the middle of the duct height.
As reference value of mean velocity the electro-potential probe (Vives-probe [6]) readings were used. The Vives probe is a contact local velocity measurement method, so the inserted in liquid metal part of the probe (diameter 5 mm) was also used for experiment as artificial disturbances generator to create Karman Street and was situated before both flow meters according to flow direction.
Under naturally appeared disturbances I mean the Vives-probe positioned between two flow meters, so it does not create disturbances that can be used as tracking particles for both and, moreover, implies additional noise effect. But even in this case I have measured effective signals and can estimate velocity. The detected disturbances are created due to duct geometry – sharp duct turns, including heat exchanger plate, electromagnetic fluctuations caused by rotation of the pump, etc.
Measurement system and signal processing improvement enabled to estimate mean velocity of liquid metal in the duct (figure 2). Electromagnetic pump creates flow within the duct, so its rotation frequency is used as horizontal coordinate to refer velocity.
The measurement results show high error value, as one can see by error bars on all four diagrams. This is observed due to low signal-to-noise ratio. More specifically, signal is getting lost against the background noise, what is easy to see on comparison between cross-correlation function of two signals and their autocorrelation function: if peaks of cross- and auto-correlations coincide we can detect only noise.
Another observation, that can be made due to presented diagrams – the time-of-flight velocity value mostly lays lower than measurement results of Vives-probe. This can be explained by the velocity difference between mean flow in the duct centre and moving vortices or other disturbances that are slowed down according to their size and direction by boundary layers or internal friction in liquid.

3. Conclusions
Experimental research of time-of-flight Lorentz force velocimetry is very challenging and interesting task. And the method itself is a prospective technique for mean velocity and volumetric flow rate measurements especially in relation to its industry applications. This method is successfully used in laboratory conditions for flow control of turbulent liquid metal and gained results show sufficient correlation between time-of-flight and reference velocity estimation without applying any additional experimental coefficient. The time-of-flight Lorentz force velocimetry doesn't directly depend on

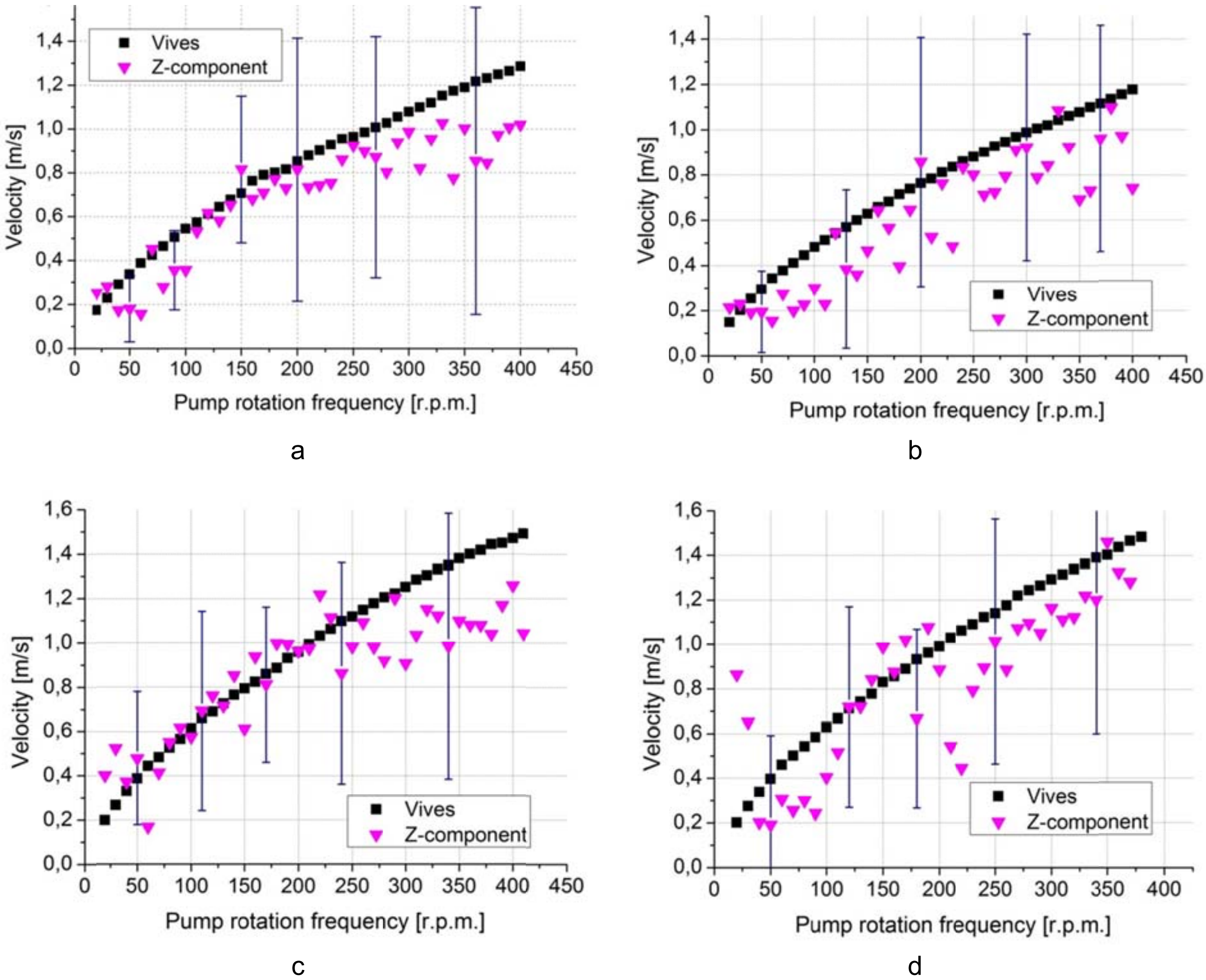


Figure 2. Time-of-flight measurements results in comparison with reference method – Vives-probe. Velocity on (a) and (b) are presented for normal position of sensors with and without artificial vortex generation correspondingly; (c) and (d) present half position sensors with and without artificial vortex generation

physical properties of liquid metal and gives wide opportunities to investigate turbulent duct flow under moderate, high Reynolds number in the sense of behaviour of vortices of different nature.

4. References

[1] Davidson, P.A. An introduction to Magnetohydrodynamics, 2001. Cambridge: Cambridge University Press, 432.

[2] Shercliff, J.A. The theory of electromagnetic flow-measurement, 1962. Cambridge: Cambridge University Press, 146.

[3] Jian, D., Karcher, Ch., Electromagnetic flow measurements in liquid metals using time-of-flight Lorentz force velocimetry. 2012 *Meas. Sci. Technol.* **23** (7).

[4] H. Yu, D. Li, R. C. Roberts, K. Xu and N. C. Tien A time-of-flight flow sensor for the volume measurement of trace amount of interstitial fluid. 2012 *J. Micromech. Microeng.* **22** 055009.

[5] Burgess Thomas H., patent US 3874234 A Vortex shedding flowmeter Fischer & Porter C0., Warminster 1975.

[6] Ricou R, Vives C Local velocity and mass transfer measurements in molten metals using an incorporated probe. 1982 *Int J Heat Mass Transfer* **25**: 1579–1588.